

# Transiting exoplanets from the CoRoT space mission<sup>\*</sup>

## XVIII. CoRoT-18b: a massive hot jupiter on a prograde, nearly aligned orbit

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### ABSTRACT

We report the detection of CoRoT-18b, a massive hot jupiter transiting in front of its host star with a period of  $1.9000693 \pm 0.0000028$  days. This planet was discovered thanks to photometric data secured with the CoRoT satellite combined with spectroscopic and photometric ground-based follow-up observations. The planet has a mass  $M_p = 3.47 \pm 0.38 M_{\text{Jup}}$ , a radius  $R_p = 1.31 \pm 0.18 R_{\text{Jup}}$ , and a density  $\rho_p = 2.2 \pm 0.8 \text{ g/cm}^3$ . It orbits a G9V star with a mass  $M_* = 0.95 \pm 0.15 M_{\odot}$ , a radius  $R_* = 1.00 \pm 0.13 R_{\odot}$ , and a rotation period  $P_{\text{rot}} = 5.4 \pm 0.4$  days. The age of the system remains uncertain, with stellar evolution models pointing either to a few tens Ma or several Ga, while gyrochronology and lithium abundance point towards ages of a few hundred Ma. This mismatch potentially points to a problem in our understanding of the evolution of young stars, with possibly significant implications for stellar physics and the interpretation of inferred sizes of exoplanets around young stars. We detected the Rossiter-McLaughlin anomaly in the CoRoT-18 system thanks to the spectroscopic observation of a transit. We measured the obliquity  $\psi = 20^\circ \pm 20^\circ$  (sky-projected value  $\lambda = -10^\circ \pm 20^\circ$ ), indicating that the planet orbits in the same way as the star is rotating and that this prograde orbit is nearly aligned with the stellar equator.

**Key words.** stars: planetary systems - techniques: photometry - techniques: radial velocities - techniques: spectroscopic

### 1. Introduction

Out of the  $\sim 550$  exoplanets known to date, more than 100 transit their parent stars as seen from the Earth. This particular configuration allows numerous key studies, including accurate radius, mass, and thus density measurements (see, e.g., Winn 2010a for a review), atmospheric studies in absorption through transits and in emission through occultations (e.g. Vidal-Madjar et al. 2003; Wheatley et al. 2010), dynamic analyses through possible timing variations (e.g. Holman et al. 2010), or spin-orbit alignment measurements thanks to the Rossiter-McLaughlin effect (e.g. Bouchy et al. 2008). The power of these analyses incited numerous search surveys for transiting planets. Most of them were discovered in the last five years, and the detection rate is still increasing.

The CoRoT space mission (*CO*nvection *RO*tation and *PL*anetary *TR*ansits, Baglin et al. 2009) was launched on 2006 December 27. Based on a 27-cm telescope and a  $2.8^\circ \times 2.8^\circ$ -field camera, it is designed to study asteroseismology and detect transiting exoplanets. The satellite al-

lows several thousand stars ( $V = 12 - 16$ ) to be continuously observed for up to 150 days with a high photometric accuracy. CoRoT is thus well adapted to detecting transiting planets with small radii, such as CoRoT-7b (Léger et al. 2009; Queloz et al. 2009), or on long orbital periods, such as CoRoT-9b (Deeg et al. 2010). It can also detect hot jupiters, such as CoRoT-18b. We report its discovery here.

We describe in Sect. 2 the CoRoT observations and the transit detection of the planetary candidate. Then, we present in Sect. 3 the ground-based follow-up observations that were needed to establish the planetary nature of the event detected by CoRoT and also to characterize this planetary system. The analysis of the whole dataset and the results are presented in Sect. 4, before conclusion in Sect. 5.

### 2. CoRoT observations and transit detection

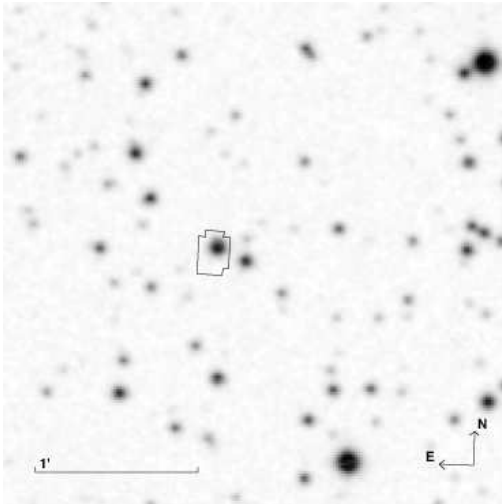
CoRoT-18 was one of 4161 target stars observed by CoRoT from 2010 March 5 to 29 as part of SRa03, the third short run of the satellite in the Galactic anti-center direction. The coordinates, magnitudes and identifiers of CoRoT-18 in various catalogs are given in Table 1. The finding chart is plotted in Fig. 1. Following the method described in Gandolfi et al. (2008), the distance,  $d$ , and interstellar extinction,  $A_V$ , to CoRoT-18 were derived using the DENIS and 2MASS magnitudes reported in Table 1 and synthetic

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<sup>\*</sup> The CoRoT space mission, launched on 2006 December 27, has been developed and is operated by CNES, with the contribution of Austria, Belgium, Brazil, ESA (RSSD and Science Programme), Germany and Spain.

**Table 1.** CoRoT-18 IDs, coordinates and magnitudes.

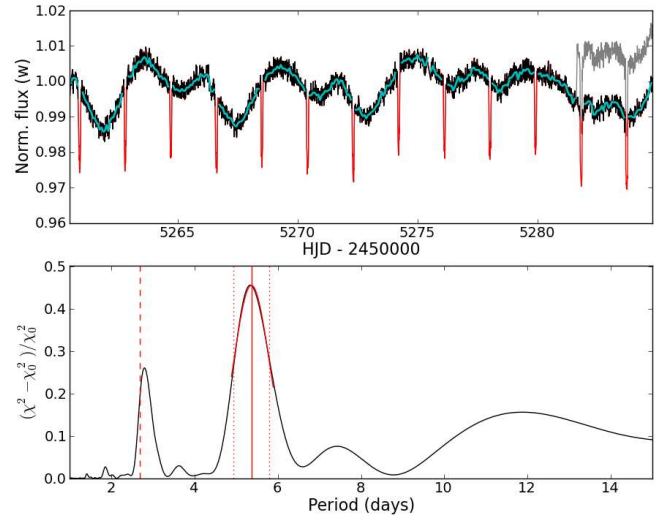
CoRoT window ID	SRa03_E2_1347	
CoRoT ID	315211361	
USNO-B1 ID	0899-0092144	
2MASS ID	06324137-0001537	
CMC14	063241.3-000153	
Coordinates		
RA (J2000)	06 <sup>h</sup> 32 <sup>m</sup> 41 <sup>s</sup> .36	
Dec (J2000)	−00° 01′ 53″.71	
Magnitudes		
Filter	Mag	Error
B2 (USNO-B1)	15.79	-
R2 (USNO-B1)	14.99	-
V	15.00	0.10
R (CMC14)	14.472	0.048
I (DENIS)	14.051	0.030
J (2MASS)	13.441	0.024
H (2MASS)	13.080	0.031
K (2MASS)	13.014	0.030

**Fig. 1.** The sky area around CoRoT-18 on the POSS red image. The target is in the middle of the image, with the overplot of the CoRoT photometric aperture mask.

colors from a model atmosphere with the same parameters as the star (see Sect. 4.2 and Table 3 below). We found  $A_V = 0.15 \pm 0.15$  mag and  $d = 870 \pm 90$  pc, as well as  $V = 15.00 \pm 0.10$  in the Johnson standard system.

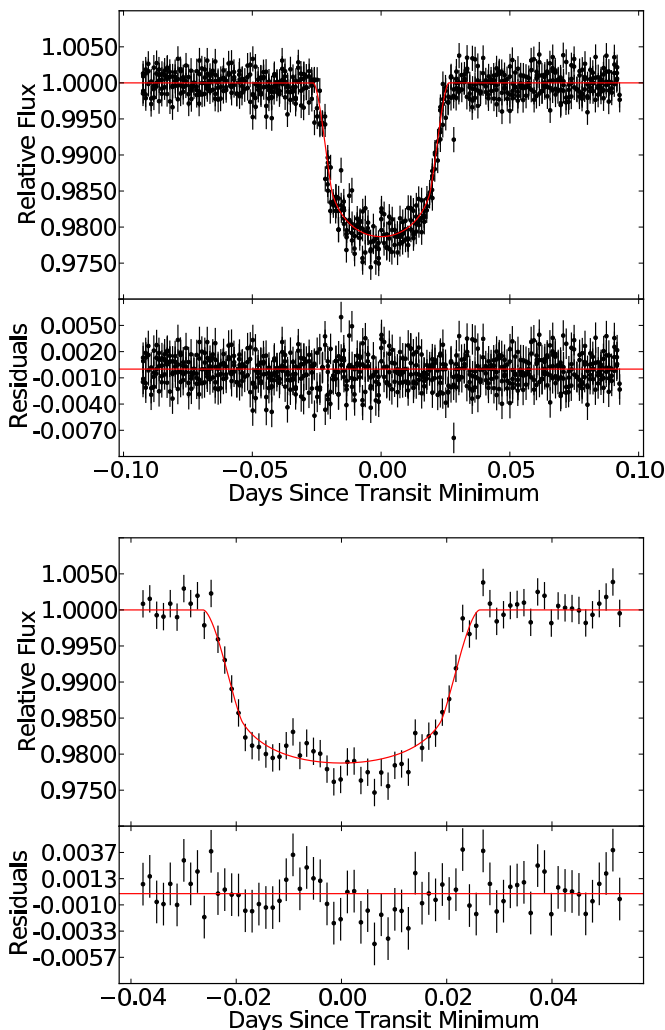
The cadence for this target was 32 seconds throughout the CoRoT observations, resulting in 65120 exposures spanning the wavelength range 300-1000 nm. The data were processed by the CoRoT pipeline (Auvergne et al. 2009). The normalized white-light curve, obtained by summing the flux from the three channels and normalizing by the mean flux, is shown in the top panel of Fig. 2. It clearly shows 13 planetary-like transit features, with a period of  $\sim 1.9$  days and a depth of  $\sim 2\%$ . The phase-folded light curve is plotted in the upper panel of Fig. 3.

To reduce computing time, the data was rebinned to 512 seconds, which is the normal observing cadence for CoRoT exoplanet targets. This binned light curve is used throughout the rest of this paper. We checked that this binning does not significantly affect the parameter retrieval

**Fig. 2.** *Top:* CoRoT light curve in black with the 13 transits shown in red. All epochs in this paper are given in Heliocentric Julian Date ( $HJD_{UTC}$ ; Eastman et al. 2010). The original light curve (shown in gray) contained a discontinuity at  $HJD - 2450000 = 5281.62$ , which was corrected by subtracting 15 mmag from data taken after this date. A linear fit to the light curve has also been used to remove any trend on timescales longer than the duration of the run. The light curve overplotted in blue is binned to one point per orbital period of the CoRoT satellite to make sure that no systematics from the rotation period can come through. *Bottom:* Lomb-Scargle periodogram of the out-of-transit light curve (black curve in top panel) as a function of relative improvement in  $\chi^2$  compared to a constant flux model. It shows the stellar rotation signature at  $5.4 \pm 0.4$  days (solid red line), as well as its first harmonic (dashed red line). Also shown are the Gaussian fit used to estimate the uncertainty in the stellar rotation period and the resulting 1- $\sigma$  interval (dotted red lines).

by using the formalism presented by Kipping (2010b). The mean flux was  $57366.4 e^-$  per 32-second exposure, and the relative standard deviation of the binned light curve is  $6.9 \times 10^{-3}$ , a factor 7.2 above the photon noise. This factor reduces to 1.6 when the transits are removed and variations on timescales longer than a day are filtered out (black line in upper panel of Fig. 2; see below Sect. 4.1).

CoRoT-18 was one of ten objects of interest identified soon after the end of SRa03 observations by the “alarm mode” pipeline (Surace et al. 2008), which removes the outliers flagged by the main pipeline, detrends the light curves to remove long-term trends (instrumental and stellar) using a median filter, and searches for transits using an implementation of the box least squares (BLS) algorithm of Kovács, Zucker & Mazeh (2002). A number of tests were then carried out to check that the CoRoT data were compatible with a planetary origin for the transits: full transit fits to the white, red, green, and blue light curves using the transit formalism of Mandel & Agol (2002), check for differences in depth between odd- and even-numbered transits, search for possible companion occultation at the transit antiphase, and search for ellipsoidal variations. Because this candidate



**Fig. 3.** Phase-folded CoRoT (top panel) and Euler (bottom panel) transit light curves with the best fit and the residuals. CoRoT data cover 13 transits with a 512-second bin and the Euler data one transit with a  $\sim 3$ -minute bin. Both datasets are joint-fitted (see Sect. 4.1).

passed all these tests, it was put forward for follow-up observations with high priority.

### 3. Ground-based follow-up observations

#### 3.1. “On-off” photometry

The point spread function of CoRoT that contains 50% of the flux has an elongated shape of about  $35'' \times 23''$ . The photometry is done through an aperture of that size. Owing to this poor spatial resolution, a deep stellar transit diluted in the flux of other source(s) also included in the large CoRoT aperture could mimic a shallow planetary transit. “On-off” photometry of the transit performed from the ground with a telescope allowing higher spatial resolution could identify contaminated eclipsing binaries (Deeg et al. 2009).

“On-off” photometric observations of CoRoT-18 were performed in November 2010 with the ESA Optical Ground Station (OGS) 1-m telescope, located at Izaña in Tenerife (Spain). Alternated short exposures of 30 seconds and long exposures of 100 seconds were taken, for a total dura-

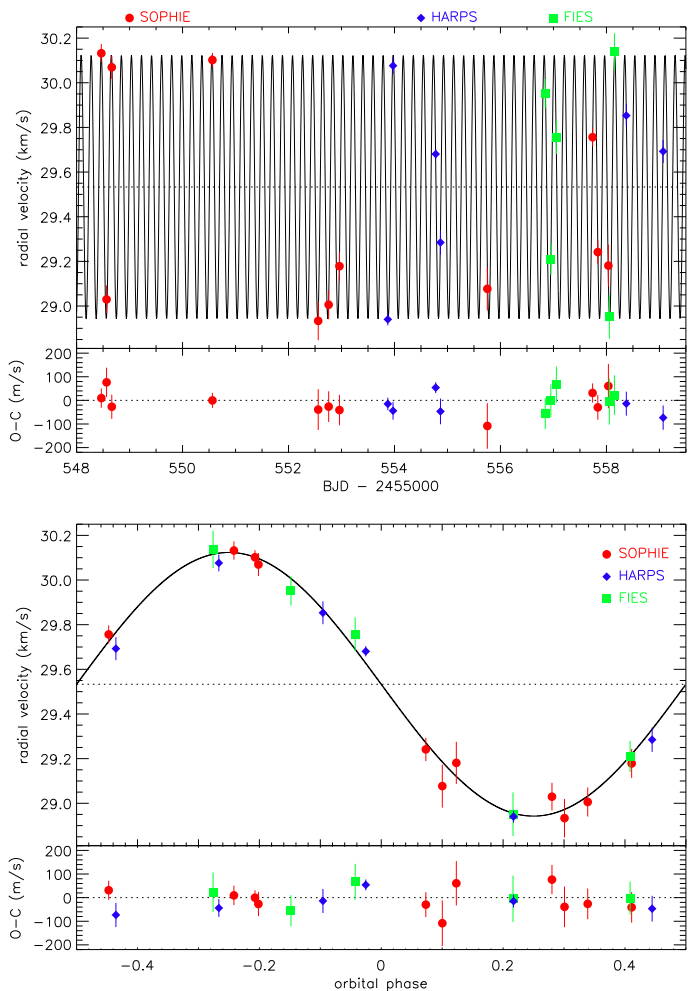
tion of 28-min observation on-transit and 28-min observation off-transit. Seven extra sources are detected in a radius of  $30''$  around the main, brighter target. We performed aperture photometry of the target and neighboring stars. The main target shows a transit with a depth  $0.03 \pm 0.01$  mag, in agreement with the transit detected with CoRoT. The seven other targets show stable fluxes, within precisions ranging from 0.01 to 0.39 mag, depending on the target and the exposure time. This “on-off” observations thus allowed us to exclude the detected transit signature caused by an eclipsing binary diluted in the CoRoT point spread function.

#### 3.2. Radial velocities

We started the spectroscopic follow-up of CoRoT-18 in October 2010 with the SOPHIE spectrograph at the 1.93-m telescope of Haute-Provence Observatory, France. Three measurements performed in three successive nights near extreme phases (assuming a circular orbit) showed large radial velocity variations, in phase with the CoRoT ephemeris. The variation was on the order of  $1 \text{ km s}^{-1}$ , indicating a companion with a mass around  $3 M_{\text{Jup}}$ . Thus we decided to pursue the spectroscopic observations with SOPHIE to strengthen the detection and to characterize the planetary system. We also used the HARPS spectrograph at the 3.6-m ESO telescope in La Silla, Chile, and the 2.56-m FIES spectrograph attached at the Nordic Optical Telescope in La Palma, Spain. Having three ground-based instruments at different longitudes was useful for reaching a good phase coverage for this system, which has an orbital period close to an integer number of terrestrial days. The observations were conducted up to January 2011, in good enough weather conditions to allow satisfactory data to be secured in reasonable exposure times for this faint target.

Both SOPHIE (Bouchy et al. 2009) and HARPS (Mayor et al. 2003) are cross-dispersed, environmentally stabilized echelle spectrographs dedicated to high-precision radial velocity measurements. SOPHIE data were acquired in High-Efficiency mode (resolution power  $R = 40\,000$ ) and HARPS data in standard HAM mode ( $R = 115\,000$ ). The spectra extraction was performed using the SOPHIE and HARPS pipelines. Following the techniques described by Baranne et al. (1996) and Pepe et al. (2002), the radial velocities were measured from a weighted cross-correlation of the spectra with a numerical mask. We used a standard G2 mask that includes more than 3500 lines. The resulting cross-correlation functions were fitted by Gaussians to get the radial velocities and the associated photon-noise errors. The full width at half maximum of those Gaussians is  $12.6 \pm 0.2 \text{ km s}^{-1}$ , and its contrast is  $27.7 \pm 0.8 \%$  of the continuum in the case of the HARPS data. The SOPHIE data gave similar parameters. We adjusted the number of spectral orders used in the cross-correlation in order to reduce the dispersion of the measurements. Indeed, some spectral domains are noisy, so using them degrades the accuracy of the radial velocity measurement. We finally used the orders 10 to 38 for SOPHIE, and 5 to 71 for HARPS.

Moonlight contamination was clearly visible in some spectra and in some cases at a radial velocity close to that of the target. Such contamination can affect the radial velocity measurements. Following the method described in Pollacco et al. (2008) and Hébrard et al. (2008), we estimated and corrected the Moon contamination by using the



**Fig. 4.** *Upper panel:* Radial velocity measurements of CoRoT-18 with  $1\text{-}\sigma$  error bars as a function of time together with their Keplerian fit (*top*) and residuals of the fit. The fit is described below in Sect. 4.4. *Lower panel:* Same as above but as a function of the orbital phase. The data are from SOPHIE (red circles), HARPS (blue diamonds), and FIES (green squares).

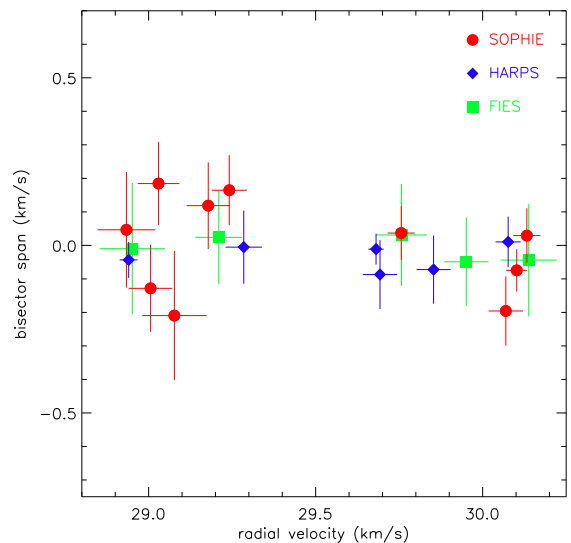
second optical-fiber aperture, which is targeted on the sky for both SOPHIE and HARPS, whereas the first aperture points toward the target. This induces radial velocity corrections up to  $400\text{ m s}^{-1}$ .

The FIES observations were performed in January 2011 under clear and stable weather conditions with seeing typically in the range  $0''.8\text{--}1''.0$ . We used the  $1''.3$  high-resolution fiber giving a resolving power  $R \simeq 67\,000$ . Following the observing strategy described in Buchhave et al. (2010), three consecutive science exposures of 20 minutes were recorded for each observing night immediately preceded and followed by one long-exposed ThAr spectrum. Data reduction and spectra extraction were performed using standard IRAF routines. Finally, the FIES radial velocity measurements of CoRoT-18 were derived cross-correlating the science spectra with the spectrum of the radial velocity standard star HD 50692 (Udry et al. 1999) observed with the same instrument set-up.

The log of the observations and the radial velocity measurements are reported in Table 2. Radial velocity measurements have accuracies ranging between  $23$  and  $98\text{ m s}^{-1}$  depending on the observing parameters. This table also shows the bisector spans that we measured on the cross-correlation functions in order to quantify the possible shape variations of the spectral lines. One SOPHIE spectrum was too polluted by the Moon to allow any accurate bisector measurement.

The radial velocity variations agree with Doppler shifts caused by a planetary companion, and the transit-signal detected from the CoRoT light curve could be interpreted as coming from a massive hot-Jupiter. We designate it as CoRoT-18b hereafter.

The measurements are displayed in Fig. 4, together with their circular Keplerian fit, assuming the period and transit epoch determined by the CoRoT light curve and refined with the photometric transit observed from the ground (see Sect. 3.4). The photometric and radial velocity data show good agreement. SOPHIE and HARPS radial velocities obtained with different stellar masks (F0 or K5) produce variations with the same amplitude as obtained with the G2 mask, so there is no indication that their variations could be explained by blend scenarios implying stars of different spectral types. Similarly, the cross-correlation function bisector spans show neither variations nor trend as a function of radial velocity (Fig. 5). This reinforces the conclusion that the radial velocity variations are not caused by spectral line profile changes due to blends.



**Fig. 5.** Bisector span as a function of the radial velocities with  $1\text{-}\sigma$  error bars. The ranges have the same extents in the  $x$ - and  $y$ -axes. The data are from SOPHIE (red circles), HARPS (blue diamonds), and FIES (green squares).

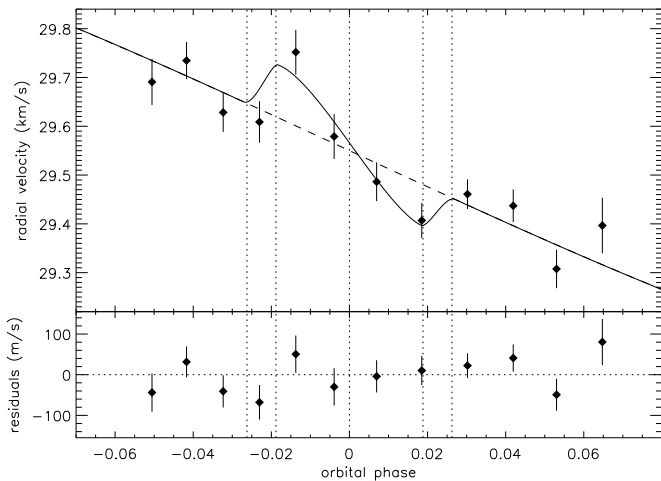
### 3.3. Transit spectroscopy

A transit of CoRoT-18b was observed in spectroscopy on 2011 January 28. The goal was to detect the Rossiter-McLaughlin anomaly, which is an apparent distortion of

the stellar lines profile because of the transit of the planet in front of the rotating star. It allows the measurement of the sky-projected angle between the planetary orbital axis and the stellar rotation axis, usually denoted  $\lambda$  (see, e.g., Bouchy et al. 2008). The spectroscopic transit was observed with HARPS in the EGGS mode to improve the throughput. By comparison to the HAM mode of HARPS used in Sect. 3.2 for the orbit determination (1" diameter fiber with a scrambler, allowing the resolution power  $R = 115\,000$  to be reached), the EGGS mode of HARPS uses a larger fiber (1"4) without scrambler. The spectral resolution is then reduced ( $R = 80\,000$ ) but the efficiency gain reaches a factor  $\sim 2$  improvement.

The target was continuously observed during a 5.5-hour sequence under good weather condition, with a seeing varying between 0"7 and 1"0. Twelve measurements were secured with exposure times ranging from 1200 to 1800 seconds, including five within the transit. The remaining observations obtained before and after the transit are mandatory for references. The radial velocities were extracted as for HARPS/HAM data (Sect. 3.2), but using fewer orders here for the cross-correlation (orders 18 to 69) to reduce the dispersion of the measurements.

The HARPS/EGGS data are plotted in Fig. 6. The Rossiter-McLaughlin anomaly is detected, with an amplitude of  $\sim 100\text{ ms}^{-1}$ , as expected according the rotation of the star and the depth of the photometric transit. The red shift during the first part of the transit and the blue shift during the second part indicate a prograde orbit. The symmetry of the feature agrees with an aligned system.



**Fig. 6.** Spectroscopic observation of the 2011 January 28 transit of CoRoT-18b. *Top:* HARPS/EGGS radial velocity measurements as a function of the orbital phase (filled diamonds), Keplerian fit ignoring the transit (dashed line), and final fit including the model of the Rossiter-McLaughlin anomaly (solid line). The vertical dotted lines show the times of mid-transit, first, second, third, and fourth contacts. *Bottom:* Residuals of the final fit.

### 3.4. Transit photometry

A transit of CoRoT-18b was observed with the Euler 1.2-m telescope on 2011 January 28 between 01:08 and 05:36 UT, roughly at the same time and location as the Rossiter-McLaughlin anomaly observed in spectroscopy with HARPS (see Sect. 3.3). The goal was to refine the ephemeris. A total of 83 frames were recorded on the recently installed 4K×4K E2V detector, with an exposure time of three minutes. As for the CoRoT light curve, we checked that this binning does not significantly affect the parameter retrieval by using the formalism presented by Kipping (2010b). Standard calibration images were taken on the same night. The fluxes from the target and 20 reference stars were extracted using standard aperture photometry with custom IDL routines. An average reference star was constructed by interactively selecting the stars that exhibited less real or instrumental variability. Nine stars were selected for this purpose. The final light curve was normalized to the median of the flux level after the egress of the transit. It is plotted in the lower panel of Fig. 3.

We considered shot noise as a first estimation of the accuracy of the measurements, which was at the level of  $10^{-3}$  for this object. The accuracy level is later re-established by an evaluation of the reduced  $\chi^2$  of the fit process to take the correlated noise present in the data into account (see Sect. 4.1). To better estimate the accuracy of the measurements, the dispersion of the data before and after the transit is  $1.7 \times 10^{-3}$ . The bump seen on the light curve near phase  $-0.01$  could hint that the planet is transiting in front of a stellar spot; however, the amplitude of this event is within an the order of magnitude of the correlated noise so a spot detection cannot be claimed here.

## 4. Analysis

### 4.1. Light curves analysis

#### 4.1.1. Initial transit fit and light curve normalization

To remove the modulations in the CoRoT light curve caused by rotating active regions on the stellar surface (see the top panel of Fig. 2), we fit second-order polynomials to stretches of data on either side of each transit spanning approximately  $-2$  to  $-1$  and  $+1$  to  $+2$  times the transit duration. These sections were then normalized and kept for further light curve fitting, while flux measurements outside were discarded from the analysis.

A detailed investigation of the immediate surroundings of the target (using Digital Sky Survey data) revealed that  $2.0 \pm 0.1\%$  of the flux in the photometric aperture was contributed by background stars. This was subtracted from the median out-of-transit flux before re-normalizing. The uncertainty in the contamination fraction translates into an effective uncertainty on the derived radius ratio due to contamination of  $\sim 0.0001$ . This is 15 times smaller than the final uncertainties derived below, so is negligible.

The transits were then modeled using the formalism of Mandel & Agol (2002), with quadratic limb darkening coefficients  $u_1$  and  $u_2$  defined according to the standard law of the form  $I(\mu)/I(1) = 1 - u_1(1 - \mu) - u_2(1 - \mu)^2$ , where  $I(1)$  and  $I(\mu)$  are the specific intensities at the center of the stellar disk and at the angle  $\theta$  between the line of sight and the emergent intensity, respectively, and  $\mu = \cos(\theta)$ . We performed an initial least-squares fit (us-

**Table 2.** Radial velocities of CoRoT-18.

HJD <sub>UTC</sub> -2 455 000	RV (km s <sup>-1</sup> )	±1 $\sigma$ (km s <sup>-1</sup> )	Bis. span (km s <sup>-1</sup> )	exp. time (sec)	S/N p. pix. (at 550 nm)	Instrument/ mode
484.6704	30.132	0.041	0.029	3600	16	SOPHIE/HE
485.6621	29.030	0.062	0.184	3600	13	SOPHIE/HE
486.6469	30.069	0.051	-0.196	3600	11	SOPHIE/HE
505.6367	30.102	0.032	-0.074	3600	15	SOPHIE/HE
525.6027 <sup>†</sup>	28.933	0.086	0.046	2802	8	SOPHIE/HE
527.5751 <sup>†</sup>	29.006	0.065	-0.128	3600	11	SOPHIE/HE
529.6121 <sup>†</sup>	29.178	0.065	0.117	3600	10	SOPHIE/HE
557.5227 <sup>†</sup>	29.077	0.096	-0.209	3600	7	SOPHIE/HE
577.3831 <sup>†</sup>	29.756	0.041	0.037	3600	16	SOPHIE/HE
578.3721 <sup>†</sup>	29.241	0.052	0.165	3600	15	SOPHIE/HE
580.3673 <sup>†</sup>	29.181	0.094	-	3600	13	SOPHIE/HE
538.7441	28.979	0.027	-0.043	3600	11	HARPS/HAM
539.7253	30.115	0.038	0.010	3600	9	HARPS/HAM
547.7838	29.720	0.023	-0.011	3600	13	HARPS/HAM
548.6767 <sup>†</sup>	29.324	0.055	-0.005	3600	7	HARPS/HAM
583.7515 <sup>†</sup>	29.892	0.051	-0.072	3200	8	HARPS/HAM
590.7061	29.732	0.051	-0.087	3600	7	HARPS/HAM
568.4512	30.075	0.066	-0.049	3600	10	FIES
569.5086	29.334	0.070	0.024	3600	8	FIES
570.5516	29.881	0.076	0.031	3600	9	FIES
580.5441	29.075	0.098	-0.010	3600	10	FIES
581.5089	30.262	0.084	-0.044	3600	11	FIES
589.5374	29.641	0.052	0.065	1200	6	HARPS/EGGS
589.5542	29.719	0.042	-0.053	1500	8	HARPS/EGGS
589.5721	29.583	0.046	-0.107	1500	8	HARPS/EGGS
589.5897	29.616	0.048	-0.037	1500	7	HARPS/EGGS
589.6074	29.727	0.051	0.046	1500	7	HARPS/EGGS
589.6261	29.596	0.052	0.156	1500	7	HARPS/EGGS
589.6467	29.501	0.045	-0.082	1800	8	HARPS/EGGS
589.6687	29.415	0.039	0.024	1800	8	HARPS/EGGS
589.6909	29.436	0.033	-0.053	1800	10	HARPS/EGGS
589.7132	29.482	0.037	-0.168	1800	9	HARPS/EGGS
589.7343	29.329	0.043	-0.236	1800	8	HARPS/EGGS
589.7565	29.435	0.065	0.002	1800	5	HARPS/EGGS

†: measurements corrected from Moonlight pollution.

ing the Levenberg-Marquardt algorithm) simultaneously to all 13 CoRoT transits, allowing the following parameters to vary: the period  $P$ , the epochs median of transit centers  $T_0$ , the planet-to-star radius ratio  $R_p/R_*$ , the impact parameter  $b$ , the scaled semi-major axis  $a/R_*$ , and the combinations of the limb darkening coefficients  $u_1 + u_2$  and  $u_1 - u_2$ . We considered a circular orbit. We discuss below the impact of possible low eccentricity on our results. The values for the limb darkening parameters obtained from this analysis were fully consistent with the values of  $u_1 = 0.47$  and  $u_2 = 0.21$  provided by Sing (2010) for a star with  $T_{\text{eff}} = 5500$  K,  $\log g = 4.5$ , and  $[M/H] = -0.1$  (see Sect. 4.2). For the remainder of our analysis, we fixed the limb darkening parameters for the CoRoT light curve to these values.

#### 4.1.2. Detailed transit fit

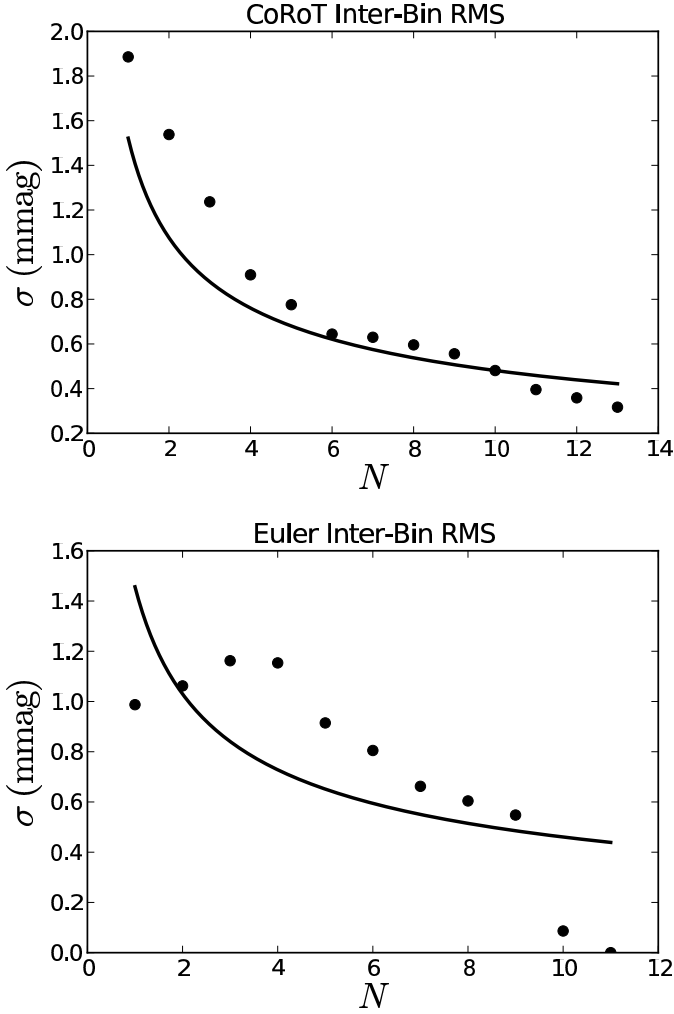
To estimate the photometric uncertainty of the CoRoT data, we calculated the standard deviation of the out-of-transit flux values, except those within 30 minutes of the ingress and egress of our initial fit. This provided an estimate of  $\sigma = 1.7$  mmag, which was then used to perform a 100 000-step Metropolis-Hastings Markov Chain Monte Carlo (MCMC) analysis with the parameters  $P$ ,  $T_0$ ,  $b$ ,

$a/R_*$ , and  $R_p/R_*$  allowed to vary, using our initial best-fit values from above as the starting points. We adjusted the jump scales for the free parameters until a step acceptance rate of 25-35% was achieved. The photometric uncertainties were then scaled up to  $\sigma = 1.9$  mmag to give a reduced  $\chi^2$  of unity for the best-fit MCMC solution. This upwards scaling of the photometric uncertainties can be attributed to the presence of correlated noise in the CoRoT light curve (Pont et al. 2006), often expressed as

$$\sigma_N^2 = \sigma_W^2/N + \sigma_R^2, \quad (1)$$

where  $\sigma_N^2$  is the variance between the mean flux values of bins containing  $N$  data points, and  $\sigma_W$  and  $\sigma_R$  represent the “white” and correlated “red” components of the noise, respectively. The uncertainty on individual flux values is then given by  $\sigma = \sigma_N$  for  $N = 1$ , so that  $\sigma = \sqrt{\sigma_W^2 + \sigma_R^2}$ . The top panel of Fig. 7 shows calculated values for  $\sigma$  as a function of  $N$  for the CoRoT light curve. The variation between the mean flux values of bins containing only a single point ( $N = 1$ ) is approximately 1.9 mmag, equal to the value that produces a reduced  $\chi^2$  of unity for the best-fit model. It also shows the expectation for a white-noise-only model that is forced to pass through the point at  $N = 10$ . For lower values of  $N$ , the white-noise-only model is not





**Fig. 7.** The standard deviation  $\sigma_N$  of measured out-of-transit flux values as a function of the number of points  $N$  for the CoRoT light curve (top panel) and the Euler light curve (bottom panel). The dark curves indicate the best-fit models without red noise, i.e. only white noise.

able to account for all of the variation in the data. This illustrates why it is necessary to scale the photometric uncertainties upwards from the standard deviation of the out-of-transit flux values.

A similar procedure was then repeated for the Euler light curve. We first estimated the photometric uncertainty to be equal to the standard deviation of the out-of-transit measured flux values, which was calculated as  $\sigma = 1.9$  mmag. We then performed a 100 000-step MCMC analysis, allowing  $P$ ,  $T_0$ ,  $b$ ,  $a/R_*$ , and  $R_p/R_*$  to vary. The limb darkening parameters  $u_1$  and  $u_2$  were also allowed to vary, but this resulted in poor chain convergence. For this reason, we decided to set their values to  $u_1 = 40$  and  $u_2 = 30$ , as provided by Claret (2004) for a star with the same parameters as above. To investigate the effect of fixing the limb darkening parameters, we experimented with fixing them to other values provided by Claret (2004) for stars with similar properties to CoRoT-18 and then performing a least squares fit to the light curve. In all cases, the fitted value for  $R_p/R_*$  changed, as expected, while the other parameters remained constant within the uncertainties. In

particular, the fitted values for  $P$  and  $T_0$  were unaffected by varying the limb darkening parameters. This is important because the primary purpose of the Euler light curve is to refine the ephemeris of the orbit (see below). We also verified that the choice of limb darkening parameters for the Euler light curve did not affect the derived values for the other parameters in the simultaneous fitting to the CoRoT and Euler light curves, which is described below. This was done by ensuring that the fitted values for  $R_p/R_*$ ,  $a/R_*$  and  $b$  remained the same regardless of whether the Euler light curve was included in the fit.

The bottom panel of Fig. 7 shows the variation between binned flux values as a function of bin number for the Euler light curve. It shows strongly correlated noise on time scales of  $\sim 10$ –20 minutes (between two to five exposures), which decreases significantly on longer timescales. This behavior is poorly modeled by Equation 1 above, with the solid line showing an illustrative fit for the white-noise-only case, i.e.  $\sigma_R = 0$ . Instead, we scaled the photometric uncertainties up to  $\sigma = 2.1$  mmag, which was the value required to give a reduced  $\chi^2$  of unity for the best-fit model.

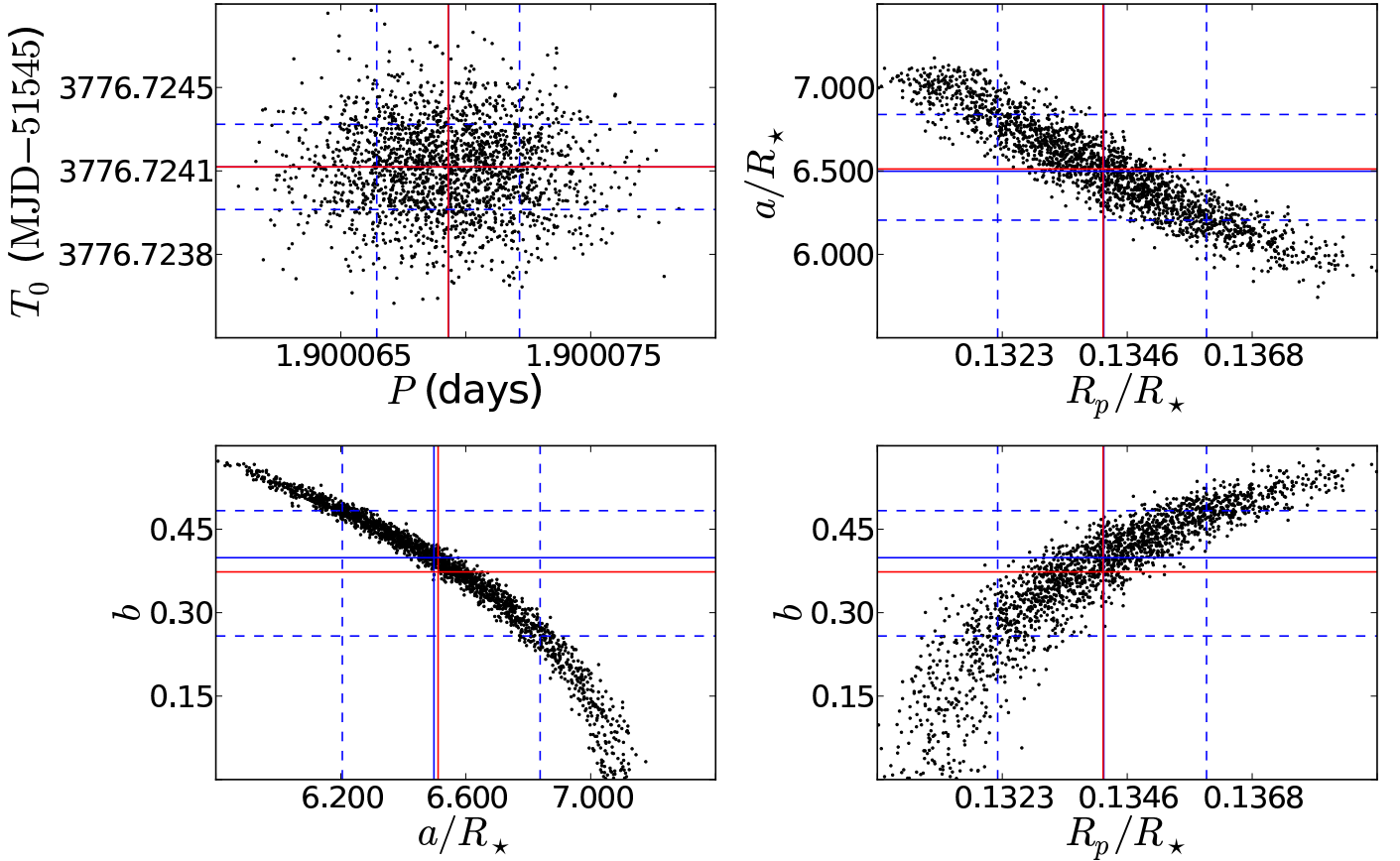
We next performed a joint MCMC analysis on the CoRoT and Euler light curves. This was done by initiating five independent chains at random locations in parameter space approximately  $\sim 5\sigma$  away from the best-fit values determined from the initial fitting process. The period was held fixed to the value determined from the initial best-fit to the CoRoT light curve, but we allowed the transit midtimes to vary for each transit in order to investigate the possibility of transit timing variations (see Sect. 4.1.3). Values for  $a/R_*$ ,  $R_p/R_*$  and  $b$  were allowed to vary with the same values across all transits, and the limb darkening coefficients were held fixed to the values described above.

The five chains were run in parallel for 200 000 steps. The initial 40 000 steps of each chain were then discarded to allow for the initial burn-in phase as the chains settled. We also checked when the  $\chi^2$  first dropped below the chain's median value, indicating the point at which the local neighborhood of the final solution had first been reached. Typically, this occurred within about 20 000 steps, implying that the truncation we made at 40 000 steps is in fact conservative. The Gelman-Rubin statistic was then calculated using the truncated chains for each of the free parameters and, in all cases, found to be within approximately 1% of unity, indicating good mixing and convergence (Gelman & Rubin 1992). The chains were then combined to obtain marginalized posterior distributions for each of the free parameters, with medians and  $1-\sigma$  uncertainties reported in Table 3 and examples plotted in Fig. 8. The upper and lower  $1\sigma$  uncertainties respectively refer to the upper and lower bounds on the intervals containing 34.1% of the chain steps on either side of the median.

A refined estimate for the orbital period was then obtained by fitting a model of the form

$$T'_0(n) = T_A + n \left( \frac{T_B - T_A}{173} \right), \quad (2)$$

where  $T'_0(n)$  denotes the transit midtime measured for the  $n^{\text{th}}$  orbit,  $T_A$  is the epoch of the first CoRoT transit and  $T_B$  is the epoch of the Euler transit, which is 173 orbital periods later. Then we ran two 200 000-step MCMC chains (one for  $T_A$  and one for  $T_B$ ) and calculated the corresponding chain for the estimated period according to



**Fig. 8.** Examples of the results of the MCMC analysis with scatter plots showing the correlations between fitted parameters. Values corresponding to the best-fit (lowest  $\chi^2$ ) solutions are indicated by red lines, while solid blue lines indicate the median values obtained for each parameter, and the dashed blue lines give the upper and lower 1- $\sigma$  uncertainties. The best and median solutions coincide for several parameters.

$P = (T_B - T_A)/173$ . As expected from Pál (2009), the correlation between  $T_A$  and  $P$  chains was negative, while the correlation between the  $T_B$  and  $P$  chains was positive. We then calculated an optimal epoch using Equation 97 of Pál (2009), which roughly corresponds to the median transit epoch, and find  $T_{\text{opt}} = T_A + 32 \times P$ . The new chain for this epoch led to the following median value for the optimal epoch, with associated 1- $\sigma$  uncertainties:  $T_0 = T_{\text{opt}} = 2\,455\,321.72412 \pm 0.00018$  HJD. By comparison to the classical computation using for example the epoch of the first transit, this method with the optimal epoch allows the uncertainty on  $T_0$  to be decreased by 2 sec, as well as the reduction of the correlation between  $T_0$  and  $P$  (see Fig. 8). The final ephemeris values are reported in Table 3 and plotted in Fig. 8. The best-fit solution for the combined data set has a reduced  $\chi^2$  of 1.01.

Finally, we estimated the effect of introducing a small eccentricity in the fit of the light curve. Indeed, Kipping (2010a) has shown that assuming  $e = 0$  for an eccentric orbit could lead to underestimated uncertainties to  $a/R_*$  ratio and stellar density  $\rho_*$ . We derive below the upper limit  $e < 0.08$  at 95% confidence from the radial velocity measurements (see Sect. 4.4). We performed new fits of the CoRoT light curve assuming this extreme eccen-

tricity, with different possible values for the longitude  $\omega$  of the periastron. Most extreme fits could provide  $a/R_*$  and  $\rho_*$  values at most to 2 $\sigma$  lower the values derived above. Thus we slightly decreased the final values on these parameters and increased their uncertainties to account for a small possible eccentricity.

#### 4.1.3. Timing analysis

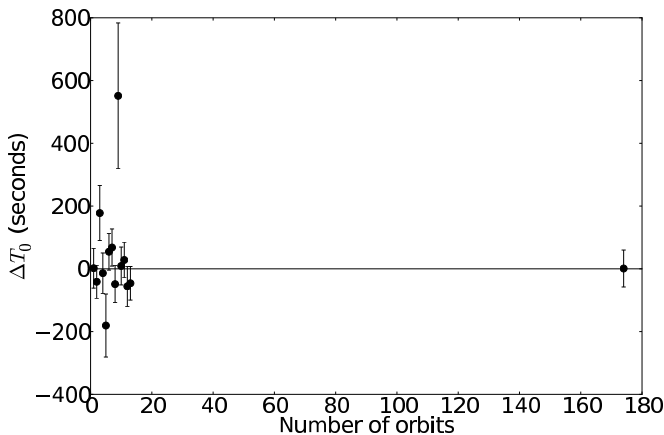
The 13 successive transits observed by CoRoT and the observation of the additional transit with Euler offer an opportunity for transit timing variations (TTVs) research (Holman & Murray 2005). Figure 9 shows the TTVs measured by

$$\Delta T_0(n) = T'_0(n) - T_0, \quad (3)$$

where  $T'_0(n)$  again denotes the transit midtime measured for the  $n^{\text{th}}$  orbit and  $T_0$  denotes the refined transit midtime derived by fitting to the ephemeris equation, as described above. We obtain a reduced  $\chi^2$  of 1.3 for the hypothesis that there are no TTVs, i.e.  $\Delta T_0(n) = 0$  for  $n = 1, \dots, 14$ . When the ninth transit is removed (visible as the most discrepant point in Fig. 9) the reduce  $\chi^2$  improves to 0.98. Inspection



of this particular transit reveals that neither the ingress nor the egress was sampled, which could help explain why the measured TTV is somewhat discrepant. This is also the case for the fifth transit. Also, it is possible that the uncertainties in the measured transit midtimes are slightly underestimated because we did not account for unocculted spots that could result in different values for the effective radius ratio  $R_p/R_*$  being measured from transit-to-transit as the spot coverage evolves; instead, we held  $R_p/R_*$  fixed for all transits in the MCMC analysis. In either case, given the perfect agreement of the Euler ephemeris with all of the other CoRoT ephemerides, we conclude that there is no evidence of TTVs in the combined data set. Given that the characteristic uncertainty on our TTV measurements was about 60 seconds, we obtain a  $3\text{-}\sigma$  TTV upper limit of 180 seconds.



**Fig. 9.** Transit timing variation  $\Delta T_0$  for each transit of CoRoT-18b. The 13 transits observed with CoRoT (on the left) were obtained about ten months before those observed with Euler (on the right). The 5<sup>th</sup> and 9<sup>th</sup> CoRoT transits do cover neither the ingress nor egress and therefore could conduct to erroneous timing measurements.

#### 4.1.4. Rotation period

The CoRoT white-light curve of CoRoT-18 shown in the top panel of Fig. 2 displays obvious signs of rotational modulation of star spots, with at least two large active regions present on the stellar surface at any one time. To estimate the rotation period we first cut out a section lasting twice the transit duration around each transit, then fit a straight line to the out-of-transit light curve to remove any long-term trend. We also corrected for a discontinuity near the end of the light curve by subtracting 15 mmag from all data taken after the discontinuity. This detrending procedure is slightly different from the one presented above in Sect. 4.1.

We estimated the rotation period by fitting sinusoids at 1000 trial periods ranging from 1 to 15 days to the corrected out-of-transit data. The resulting best-fit amplitudes are shown as a function of trial period in the bottom panel of Fig. 2. The dominant peak clearly corresponds to the interval between repeat appearances of individual active regions, hence to the rotation period. There is also signif-

icant power at the first harmonic of the rotation period. We do not expect aliases here from the CoRoT satellite orbital period, because it is well below the Nyquist sampling frequency of the data. We checked for that by binning the light curve to one point per orbital period (upper panel of Fig. 2) to make sure that no systematics from the satellite rotation period can come through, and repeated the study. The results were identical.

To refine the estimate of the rotation period, we fit a Gaussian to the periodogram around the main peak, shown in the lower panel of Fig. 2, and adopted the standard deviation of the Gaussian as our period uncertainty, yielding  $P_{\text{rot}} = 5.4 \pm 0.4$  days. This period is quite short for a late G-type star: even at the age of the Hyades, typical rotation periods for this spectral type are in the range of eight to nine days (Kawaler 1989).

#### 4.1.5. Planetary occultation upper limit

We derived the depth upper limit of a possible occultation of the planet by the star by fitting a Mandel & Agol (2002) transit model at phase 0.5, with no limb darkening and a transit depth reduced by a factor  $F_p/F_*$ , where  $F_p$  is the planetary flux and  $F_*$  the stellar flux. All parameters were kept fixed to the best-fit values derived from the transit, except for the eclipse depth, for which we obtain a best-fit value of  $0.05 \pm 0.19$  mmag, i.e. consistent with zero. The resulting  $3\text{-}\sigma$  upper limit is 0.61 mmag. This is not particularly stringent, as one can expect a planetary to star flux ratio of 0.40 mmag in the optimistic case of a geometric albedo equal to one.

#### 4.2. Stellar analysis and classification

To determine the planetary parameters with an as high as possible precision we need to know the physical conditions of its host star. Seager & Mallén-Ornelas (2003), among others, have shown that ideally there is one stellar parameter, the stellar density, which can be obtained from a transit light curve of sufficient photometric precision. From this parameter, it is possible (with a number of assumptions) to derive, through modeling, other physical parameters of the system. Nevertheless, as pointed out in this context by e.g. Fridlund et al. (2010), high-precision photometric and spectroscopic measurements that has been carried out on other exoplanet host stars, do suggest that this rarely infers reliably to the other properties of the star – mainly because of flaws in stellar theory (Winn et al. 2008).

We used the two sets of HARPS observations to perform this analysis: the HARPS/HAM data (co-addition of six spectra totaling 5.8 hours of integration, see Sect 3.2) and the HARPS/EGGS data (co-addition of 12 spectra totaling 5.4 hours of integration, see Sect 3.2). Due to its lower resolution power (80 000 *vs.* 115 000) the HARPS/EGGS data presents the higher signal-to-noise ratio ( $\sim 35$  in the continuum at  $H\alpha$ ). We analyzed both sets of observations and find no significant differences in the stellar parameters beyond the internal  $1\text{-}\sigma$  error. Three observations are immediately made while inspecting the co-added spectra. The appearance is that of a cool star, the line profiles are relatively broad ( $v \sin i_* = 8.0 \pm 1.0$  km s<sup>-1</sup>), and there is a faint absorption (equivalent width of  $\sim 40$  mÅ) at the location of the Li I (6707.8 Å) line. There is no obvious detection of

any Ca II chromospheric emission. This  $v \sin i_*$  direct measurement agrees with this derived from the cross-correlation function following the Santos et al. (2002) methodology.

To determine the spectroscopic parameters, we used the Spectroscopy Made Easy (SME, version 162, February 2011) software package (Valenti & Piskunov 1996; Valenti & Fischer 2005). SME calculates synthetic spectra and fits the observations to it. All the normal stellar parameters ( $T_{\text{eff}}$ ,  $\log g$ ,  $v \sin i_*$ ,  $[\text{Fe}/\text{H}]$ , abundances, etc.) can be used either as input or as free parameters to solve for. A grid of stellar models (Kurucz models) was utilized in order to determine the fundamental stellar parameters iteratively. This was achieved by fitting the observed spectrum directly to the synthesized spectrum and minimizing the discrepancies using a nonlinear least-squares algorithm. SME requires atomic line data in order to synthesize a spectrum. We utilized input from the Vienna Atomic Line Database (Kupka et al. 1999; Piskunov et al. 1995).

Using SME and a sample of more than 1000 stars, Valenti & Fischer (2005) found uncertainties of 44 K in  $T_{\text{eff}}$ , 0.06 dex in  $\log g$ , and 0.03 dex in  $[\text{M}/\text{H}]$  per measurement. Based on the CoRoT material (stars hosting CoRoT planets or candidates that have not been positively shown to host planets), we find slightly larger errors than Valenti & Fischer (2005): 70 – 100 K in  $T_{\text{eff}}$ , depending on the signal-to-noise in the continuum of the spectrum at the location of the Balmer lines, 0.05 – 0.1 dex in  $\log g$ , depending also on the spectral type and on which ion we used, and finally 0.05 – 0.1 dex in  $[\text{M}/\text{H}]$ . However, by comparing the measurements with model isochrones they found a larger, systematic offset of  $\sim 0.1$  dex and a scatter that can occasionally reach 0.3 dex in  $\log g$ . In CoRoT-18, we find an internal discrepancy using SME of 0.1 dex. We therefore assign 0.1 dex as our 1- $\sigma$  precision.

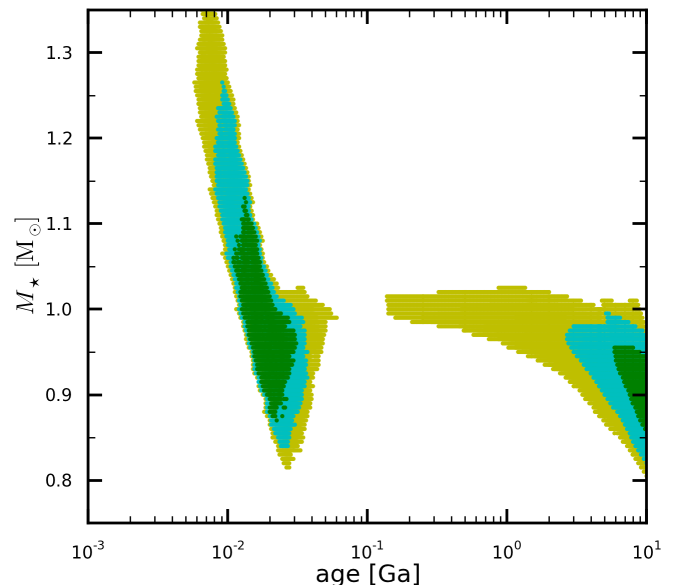
We found  $T_{\text{eff}} = 5443 \text{ K} \pm 100 \text{ K}$  from the profile of the Balmer lines. We determined the metallicity and found consistent results from different ions indicating a star of slightly lower than Solar metallicity:  $[\text{M}/\text{H}] \simeq -0.1 \pm 0.1$ . The  $\log g$  was determined utilizing the lines of Ca I, Mg I and Na I, finding a consistent result of  $4.4 \pm 0.1$ . The spectroscopic parameters of CoRoT-18 are summarized in Table 3.

#### 4.3. Stellar evolution tracks and the age problem

Altogether, CoRoT-18 seems remarkably similar to CoRoT-2 (Alonso et al. 2008): the two stars (CoRoT-18 *vs.* CoRoT-2) have comparable effective temperatures (5440 *vs.* 5450 K), metallicities ( $-0.1$  *vs.* 0.0), spin periods (5.4 *vs.* 4.5 days), and  $v \sin i_*$  (8.0 *vs.* 12  $\text{km s}^{-1}$ ), and they are both active, with peak-to-peak photometric variabilities of  $\sim 2\%$  and  $\sim 4\%$ , respectively. In addition CoRoT-18b and CoRoT-2b are the only known planets (transiting or not) orbiting a star colder than 6000 K and with a large  $v \sin i_*$ . The other planet-host stars in this temperature range all have  $v \sin i_*$  values in the range  $[0 - 5] \text{ km s}^{-1}$ . All the planet-host stars having  $v \sin i_* \sim 10 \text{ km s}^{-1}$  or larger are F-stars – except CoRoT-18 and CoRoT-2.

However, the inferred stellar densities for CoRoT-18 and CoRoT-2 ( $1.35 \pm 0.25$  *vs.*  $1.814^{+0.050}_{-0.045} \text{ g cm}^{-3}$  – see Gillon et al. 2010) slightly differ. As a result, the effective temperature, metallicity, and density constraint for CoRoT-18 are consistent with evolution tracks for solar-mass stars that are either particularly young and still on the pre-main sequence or old and towards the end of the main-sequence

evolution (see Figs. 2-4 from Guillot & Havel 2011). We used the CESAM evolution code (Morel & Lebreton 2009) to calculate these evolution tracks. In Fig. 10 we plot the solutions in the stellar-mass, age parameters, with colors that depend on their quadratic distance to the effective temperature-stellar density constraints. These point towards either a young age, less than 30 Ma (at  $3\sigma$ ), or an old one, more than 8 Ga at  $1\sigma$  and more than 4 Ga at  $3\sigma$ . The situation is thus different than for CoRoT-2, for which a continuum of young and late-type solutions was found (see Guillot & Havel 2011). For CoRoT-18, these solutions contradict with the other age indicators.



**Fig. 10.** Constraints obtained from stellar evolution models for the age and mass of CoRoT-18. The colored circles correspond to constraints derived from stellar evolution models matching the stellar density and effective temperature within a certain number of standard deviations: less than 1  $\sigma$  (green), 2  $\sigma$  (blue), or 3  $\sigma$  (yellow).

First, as for CoRoT-2, the rapid rotation of the star points towards a young age. Bouvier (2007) has compiled hundreds of rotational period measurements from photometric surveys of young open clusters with ages up to 625 Ma (Hyades), and used them to model the rotational evolution of stars in several mass bins. A range of models is needed to reproduce the data at any given age, and constraints are scarce beyond 200 Ma for stars with masses between 0.8 and  $1 M_{\odot}$ . However, extrapolation of the models calibrated at earlier ages suggests that such stars are not expected to retain rates  $\sim 5$  times faster than the Sun (which is the case for CoRoT-18) beyond ages of 500–600 Ma.

Second, the lithium equivalent width favors the latter end of this age range. According to a recent compilation of Li depletion measurements, also from stars in young open clusters (Hillenbrand et al. 2009), the equivalent width of 40 mÅ measured for CoRoT-18 is typical of stars of this spectral type at the age of Ursa Majoris (500 Ma) or the Hyades (625 Ma), while typical equivalent widths for similar stars in M34 and M7 ( $\sim 200$  Ma) are about 100 mÅ. This

would thus instead suggest an age of several hundred Ma for CoRoT-18.

Thus, for now we are unable to estimate the age of CoRoT-18, even if it seems to be young. This illustrates the difficulty in determining the age of stars. We adopt the stellar mass  $M_\star = 0.95 \pm 0.15 M_\odot$ . The conservative error bar is large enough to agree with both pre-main-sequence case and old star main-sequence star. This implies a semi-major axis  $a = 0.0295 \pm 0.0016$ , a stellar radius  $R_\star = 1.00 \pm 0.13 R_\odot$ , and thus a planetary radius  $R_p = 1.31 \pm 0.18 R_{\text{Jup}}$ . The equilibrium temperature of the planet assuming an isotropic zero-albedo is  $T_{\text{eq}} = 1550 \pm 90$  K. The rotation period  $5.4 \pm 0.4$  days (Sect. 4.1.4) is consistent with the high value  $v \sin i_\star = 8.0 \pm 1.0 \text{ km s}^{-1}$  and is fast for a late G-type star. Using  $R_\star = 1.00 \pm 0.13 R_\odot$ , this translates into an inclination of the stellar rotation axis that is  $i_\star = 70^\circ \pm 20^\circ$ , so the star is seen nearly edge-on.

#### 4.4. Radial velocities fit

We fitted the radial velocities with a Keplerian model. The period and the epoch of the transit were fixed to the values obtained from the light curves analysis (Sect. 4.1). If the relative accuracy of the radial velocity measurements is high (a few tens of  $\text{m s}^{-1}$  here in the case of CoRoT-18), their absolute accuracy in heliocentric or barycentric frames could be ten times less good, so a radial velocity shift was free to vary in the fit between the three datasets used for the orbit (SOPHIE, HARPS/HAM, and FIES), and we finally obtained one systemic radial velocity for each of the three instruments. The HARPS/EGGS data secured during a transit do not significantly constrain the orbit, and they are used below for the analysis of the Rossiter-McLaughlin anomaly. We found the upper limit  $e < 0.08$  at 95% confidence for the eccentricity of the orbit and thus assumed a circular orbit, as usually is the case for hot jupiters. In the case of a slightly eccentric orbit, its orientation is not well constrained, with the longitude of the periastron included in the range  $-60^\circ < \omega < 100^\circ$ .

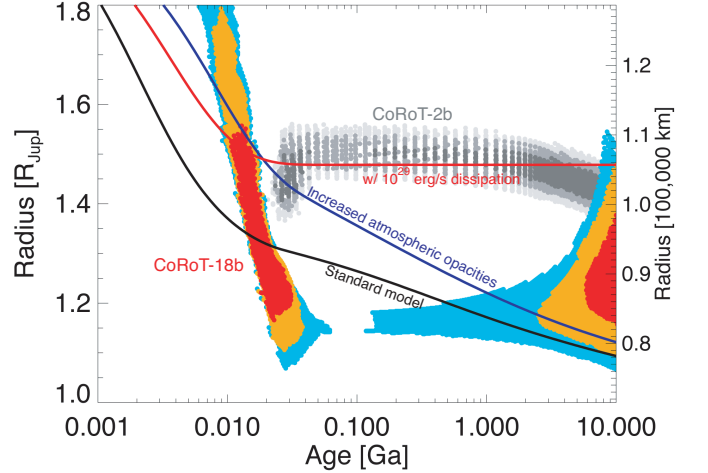
The final fit of the radial velocities is plotted in Fig. 4. The derived orbital parameters are reported in Table 3, together with error bars that were computed from  $\chi^2$  variations and Monte Carlo experiments. The radial velocity variations present a semi-amplitude  $K = 590 \pm 14 \text{ m s}^{-1}$ , corresponding to a planet with a mass  $M_p = 3.47 \pm 0.38 M_{\text{Jup}}$ . This assumes  $M_\star = 0.95 \pm 0.15 M_\odot$  for the host star, which here is the main source of uncertainty on  $M_p$ .

The standard deviation of the residuals to the fit is  $\sigma_{O-C} = 41.0 \text{ m s}^{-1}$  for the whole dataset (35.9, 44.4, and  $43.0 \text{ m s}^{-1}$  for SOPHIE, HARPS/HAM, and FIES, respectively). The reduced  $\chi^2$  is 1.02 for the 22 radial velocities used in the fit. We do not detect any drift over the 106-day span of the radial velocity, with an upper limit of  $200 \text{ m s}^{-1} \text{ a}^{-1}$  at 95% confidence. We can thus exclude any extra planet in the system with a mass higher than  $3 M_{\text{Jup}}$  and a period shorter than 200 days.

#### 4.5. Planetary evolution

We have seen that CoRoT-18 and CoRoT-2 are similar for what concerns their stars. Their planets (CoRoT-18b vs. CoRoT-2b) are also strikingly similar, in terms of orbital periods (1.90 vs. 1.74 days), masses (3.4 vs.  $3.7 M_{\text{Jup}}$ ), and

equilibrium temperatures (1550 vs. 1539 K). The inferred planetary radii are  $1.31 \pm 0.18 R_{\text{Jup}}$  for CoRoT-18b and  $1.466^{+0.042}_{-0.044} R_{\text{Jup}}$  for CoRoT-2b (Gillon et al. 2010).



**Fig. 11.** Constraints obtained on the age and radius of CoRoT-18b. The colored circles correspond to  $1\sigma$  (red),  $2\sigma$  (yellow), or  $3\sigma$  (blue) solutions. The figure also plots the same constraints for CoRoT-2b (grayscale), when not including the effects of spots (see Czesla et al. 2009, Guillot & Havel 2011). The evolution tracks show the progressive contraction of a  $3.5 M_{\text{Jup}}$  planet with  $T_{\text{eq}} \sim 1600$  K, in the so-called “standard approach”, when increasing atmospheric opacities by a factor 3.5, and when dissipating  $10^{29} \text{ erg s}^{-1}$  at the center (see Guillot & Havel 2011 for a description of the models).

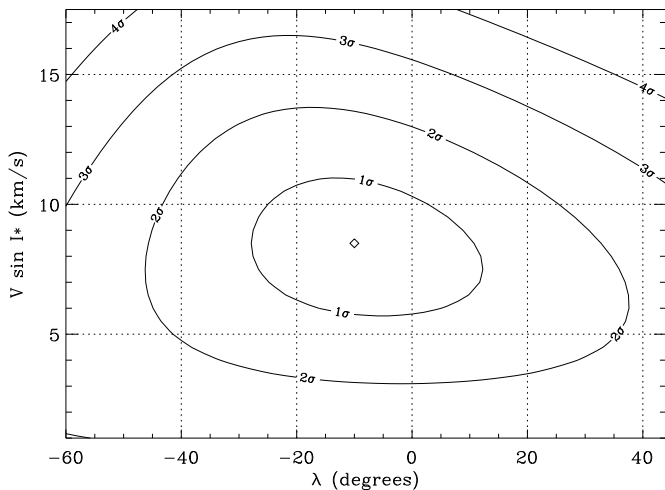
Figure 11 compares the planetary radii obtained as a function of age for the two planets, using the approach described in Guillot & Havel (2011). To use the same approach for the two planets, when calculating the size of CoRoT-2b, we did not account for the effect of spots (see Czesla et al. 2009, Guillot & Havel 2011) – in the case of CoRoT-2b, these yield a  $\sim 3\%$  increase in the inferred radius. For CoRoT-2b, the age constraints from evolution models matching ( $T_{\text{eff}}$ ,  $\rho_*$ ,  $\log g$ ,  $[\text{Fe}/\text{H}]$ ) are weak and  $3\sigma$  solutions are found anywhere between 20 Ma to more than 15 Ga). The inferred radius is extremely large for an object of this mass and planetary evolution models require a recent ( $\sim 20$  Ma) dramatic event (birth, giant impact, close encounter, and circularization of the orbit) to explain it. Because of its lower stellar density, solutions for CoRoT-18 are found at both extremes of the age range (10 to 25 Ma and more than 4 Ga, see Sect. 4.3). The constraints on the size of CoRoT-18 are weaker so that they cannot be used to confirm or refute possible inflation mechanisms or possible compositions, at least as long as the cause of the age mismatch between stellar evolution models and youth indicators (see Sect. 4.3) is not found.

If the mismatch found for CoRoT-18 between the various age indicators can be linked to the poorly known physics of young stars, it may lead to completely reconsider the problem of the inflated size of CoRoT-2b and other exoplanets orbiting young stars.

#### 4.6. Rossiter-McLaughlin anomaly analysis

The radial velocity measured during the 2011 January 28 transit were fitted in order to derive the sky-projected angle  $\lambda$  between the planetary orbital axis and the stellar rotation axis. We applied the analytical approach developed by Ohta et al. (2005) to model the Rossiter-McLaughlin anomaly shape, which use here ten parameters: the stellar limb-darkening linear coefficient  $\epsilon$ , the transit parameters  $R_p/R_*$ ,  $a/R_*$  and  $i$ , the parameters of the circular orbit ( $P$ ,  $T_0$ , and  $K$ ), the HARPS/EGGS systemic radial velocity, and finally  $v \sin i_*$  and  $\lambda$ . We adopted  $\epsilon = 0.722$  computed by Claret (2004) in the  $g'$  filter corresponding to the HARPS wavelength range. The transit and orbital parameters were determined above from the light curves and radial velocity fits, and their uncertainties are negligible for the fit of the Rossiter-McLaughlin anomaly shape, according the uncertainties of the HARPS/EGGS radial velocities. The main parameters that play a role in this fit are the systemic velocity,  $\lambda$ , and  $v \sin i_*$ . As these parameters are correlated in the Rossiter-McLaughlin fit, we computed the  $\chi^2$  of the fit on a three-dimensional grid scanning their possible values.

The systemic velocity we obtained for the transit observed with HARPS/EGGS,  $29.550 \pm 0.016$ , is similar to this obtained in Sect. 4.4 for the orbit observed with HARPS/HAM. It is constrained thanks to the observations secured immediately before and after the transit. The confidence interval contours estimated from  $\chi^2$  variations for the  $\lambda$  and  $v \sin i_*$  are plotted in Fig. 12. We thus obtained  $\lambda = -10^\circ \pm 20^\circ$  and  $v \sin i_* = 8.5 \pm 2.5 \text{ km s}^{-1}$ . The best fit is plotted in Fig. 6. The dispersion of the residuals to the fit is  $46.5 \text{ m s}^{-1}$ . This agrees with the expected error bars on the radial velocities, and this is similar to the dispersion of the residuals to the fit of the orbit presented in Sect. 4.4.



**Fig. 12.**  $\chi^2$  isocontours for our modeling of the Rossiter-McLaughlin effect as a function of  $\lambda$  and  $v \sin i_*$ . The diamond shows the lowest- $\chi^2$  value.

The Rossiter-McLaughlin anomaly detection only stands on a few points; however, the shape of the radial velocity variations during the transit agree with a Rossiter-McLaughlin feature, with  $\lambda \simeq 0^\circ$  and the ex-

pected amplitude. As a statistical test for the Rossiter-McLaughlin anomaly detection, we computed the  $\chi^2$  over the 12 measurements secured during the transit night, and we get 12.5 and 24.7 for the fits including or not the Rossiter-McLaughlin anomaly, respectively. Including the Rossiter-McLaughlin model in the fit thus implies a factor two improvement in the  $\chi^2$ , for basically two extra free parameters ( $\lambda$  and  $v \sin i_*$ , which mainly constraints the Rossiter-McLaughlin shape). We performed an F-test which indicates there is a probability  $> 70\%$  that the  $\chi^2$  improvement actually is due to the Rossiter-McLaughlin anomaly detection.

Usually only the sky-projected value  $\lambda$  of the obliquity  $\psi$  could be measured because the inclination  $i_*$  of the stellar rotation axis remains unknown. Here we estimated  $i_* = 70^\circ \pm 20^\circ$  (Sect. 4.2), so the sky-projected  $\lambda$  could be translated into the actual obliquity. We obtain  $\psi = 20^\circ \pm 20^\circ$ . This value remains inaccurate, due to the significant uncertainties on  $\lambda$  and  $i_*$ . It allows, however, the conclusion that the orbit of CoRoT-18b is prograde and nearly aligned. This additionally reinforces the similarity between the CoRoT-18 and CoRoT-2 planetary systems, since CoRoT-2b is also prograde and aligned (Bouchy et al. 2008).

The  $v \sin i_*$  value obtained from this fit agrees with this obtained in Sect. 4.2 from spectral analysis,  $v \sin i_* = 8.0 \pm 1.0 \text{ km s}^{-1}$ . As discussed by, e.g., Hirano et al. (2010) and Simpson et al. (2011), modeling the Rossiter-McLaughlin anomaly could produce biased  $v \sin i_*$  measurements when rotational broadening of the stellar lines is significantly larger than the instrument resolution. We do not see that effect here, possibly because of the long exposure times of each exposure.

## 5. Conclusion

We reported the detection of the 18<sup>th</sup> transiting exoplanet detected by the CoRoT project. This giant planet was discovered thanks to the high-accuracy, continuous photometry obtained by the CoRoT satellite and the photometric and spectroscopic follow-up performed on ground-based telescopes. CoRoT-18b is a massive hot jupiter orbiting a faint G9V star. Its mass is  $M_p = 3.47 \pm 0.38 M_{\text{Jup}}$ , and its radius  $R_p = 1.31 \pm 0.18 R_{\text{Jup}}$ , implying a density  $\rho_p = 2.2 \pm 0.8 \text{ g cm}^{-3}$ . The period of the circular orbit is  $1.9000693 \pm 0.0000028$  days. It is known with an accuracy better than 0.25 seconds and the mean mid-transit epoch with an accuracy of 20 seconds. The mass of the host star is  $M_* = 0.95 \pm 0.15 M_\odot$  and its radius  $R_* = 1.00 \pm 0.13 R_\odot$ . The parameters of this system are summarized in Table 3.

The parameters of CoRoT-18b are similar to those of CoRoT-2b (Alonso 2008; Gillon et al. 2010), and to a lesser extent to those of CoRoT-11b (Gandolfi 2010) and CoRoT-17b (Csizmadia et al. 2011), the other massive hot jupiters found with CoRoT. Interestingly CoRoT-18b is found to be either particularly young (a few tens of Ma) or old ( $> 4 \text{ Ga}$ ) from stellar evolution models matching the star's effective temperature and inferred density, but according both to its lithium abundance and to its relatively fast rotation, it would be expected to be modestly young (several hundred Ma). This mismatch potentially points to a problem in our understanding of the evolution of young stars, with possibly significant implications for stellar physics and the interpretation of inferred sizes of exoplanets around young

**Table 3.** Planet and star parameters.

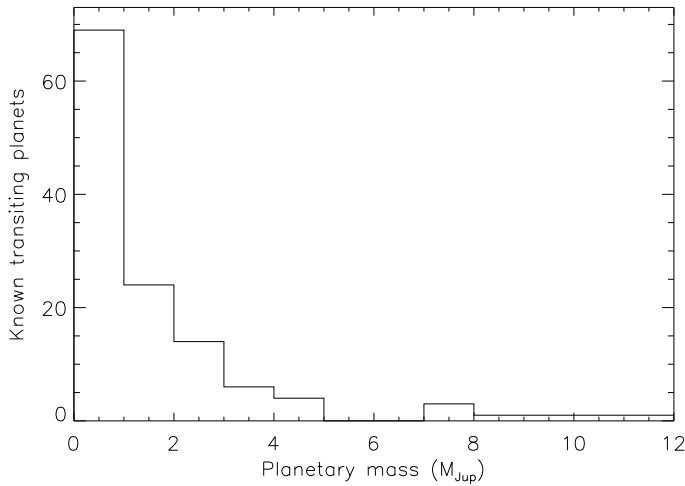
<i>Fitted transit parameters</i>	
Planet orbital period $P$ [days]	$1.9000693 \pm 0.0000028$
Transit center epoch $T_0$ [HJD]	$2\,455\,321.72412 \pm 0.00018$
Scaled semi-major axis $a/R_*$	$6.35 \pm 0.40$
Radius ratio $k = R_p/R_*$	$0.1341 \pm 0.0019$
Impact parameter $b = a \cos i/R_*$	$0.40^{+0.08}_{-0.14}$
<i>Deduced transit parameters</i>	
Orbit inclination $i$ [°]	$86.5^{+1.4}_{-0.9}$
Transit duration $T_{1-4}$ [h]	$2.387 \pm 0.037$
Egress/ingress duration $T_{1-2} = T_{3-4}$ [h]	$0.331 \pm 0.038$
$M_*^{1/3}/R_*$ [Solar units]	$0.99 \pm 0.06$
Stellar density $\rho_*$ [ $g\,cm^{-3}$ ]	$1.35 \pm 0.25$
<i>Results from radial velocity observations</i>	
Radial velocity semi-amplitude $K$ [ $m\,s^{-1}$ ]	$590 \pm 14$
Orbital eccentricity $e$	$< 0.08$
SOPHIE systemic velocity [ $km\,s^{-1}$ ]	$29.533 \pm 0.016$
HARPS/HAM systemic velocity [ $km\,s^{-1}$ ]	$29.572 \pm 0.015$
FIES systemic velocity [ $km\,s^{-1}$ ]	$29.657 \pm 0.034$
O-C residuals [ $m\,s^{-1}$ ]	41.0
<i>Spectroscopic stellar parameters</i>	
Effective temperature $T_{\text{eff}}$ [K]	$5440 \pm 100$
Surface gravity $\log g$ [dex]	$4.4 \pm 0.1$
Metallicity [Fe/H] [dex]	$-0.1 \pm 0.1$
Rotational velocity $v \sin i_*$ [ $km\,s^{-1}$ ]	$8.0 \pm 1.0$
Spectral type	G9V
Star mass [ $M_\odot$ ]	$0.95 \pm 0.15$
<i>Stellar and planetary parameters</i>	
Star radius [ $R_\odot$ ]	$1.00 \pm 0.13$
Distance of the system [pc]	$870 \pm 90$
Stellar rotation period $P_{\text{rot}}$ [days]	$5.4 \pm 0.4$
Stellar inclination $i_*$ [°]	$70 \pm 20$
Orbital semi-major axis $a$ [AU]	$0.0295 \pm 0.0016$
Planet mass $M_p$ [ $M_J$ ]	$3.47 \pm 0.38$
Planet radius $R_p$ [ $R_J$ ]	$1.31 \pm 0.18$
Planet density $\rho_p$ [ $g\,cm^{-3}$ ]	$2.2 \pm 0.8$
Equilibrium temperature $T_{\text{eq}}$ [K]	$1550 \pm 90$
<i>Rossiter-McLaughlin parameters</i>	
Sky-projected obliquity $\lambda$ [°]	$10 \pm 20$
HARPS/EGGS systemic velocity [ $km\,s^{-1}$ ]	$29.550 \pm 0.016$
O-C residuals (HARPS/EGGS) [ $m\,s^{-1}$ ]	46.5
Obliquity $\psi$ [°]	$20 \pm 20$

stars. In addition, CoRoT-18b and CoRoT-2b are the only known planets (transiting or not) orbiting a fast-rotating, G-type or cooler star.

The orbit of CoRoT-18b is prograde, with a spin-orbit angle  $\psi = 20^\circ \pm 20^\circ$  (sky-projected value  $\lambda = -10^\circ \pm 20^\circ$ ), hence an obliquity in agreement with 0. Schlaufman (2010) and Winn et al. (2010b) have shown that misaligned planets tend to orbit hot stars. With an effective temperature of  $5440 \pm 100$  K for the host star, the CoRoT-18 system supports this trend. Exceptions to this trend are increasing, however (Moutou et al. 2011; Brown et al. 2011).

Hébrard et al. (2010; 2011) have hypothesized that most of the massive planets are prograde and moderately but significantly misaligned, whereas the less massive planets are

distributed in two thirds of the prograde, aligned systems and one third of the strongly misaligned systems. Being prograde and nearly aligned, CoRoT-18b is at the upper limit of the low-mass range. Interestingly, a limit is also apparent in the mass distribution of known transiting planets. This is shown in Fig. 13, where one can see a decreasing abundance of planets with increasing planetary mass up to  $4.5 M_{\text{Jup}}$ . No transiting planets are known in the range  $M_p = [4.5 - 7] M_{\text{Jup}}$ , and a few are known with  $M_p > 7 M_{\text{Jup}}$ . It is difficult to imagine that a bias is provoking the lack of massive planets, as they are easier to detect. This different distribution suggests that planets below  $4.5 M_{\text{Jup}}$  could have a different nature or history than those above  $7 M_{\text{Jup}}$ . This is reinforced by the different obliquity distribution.



**Fig. 13.** Histogram of the number of known transiting planets as a function of their mass (data from <http://exoplanet.eu>).

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